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Development and characterization of a new silicone/platine based 2-DoF sensorized end-effector for micromanipulators

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ABSTRACT

This paper reports the development and the characterization of a new silicone end-effector with integrated sensor based on a set of platine piezoresistive gage. Used as interface between a micromanipulator or actuator and a manipulated small object, the features of the end-effector are: 1) its compactness (length between $750\mu\text{m}$ and 2mm , width= $40\mu\text{m}$, thickness= $25\mu\text{m}$), 2) the fully integrated force measurement system thanks to microfabricated platine piezoresistive gage, 3) the 2-dof (degrees of freedom: along y and z axis) measurement capability, 4) the high sensitivity of measurement provided for each axis (0.6% to 0.8% for the range of measured force of 1mN), 4) and the relatively high gauge factor ($G=6$). This paper reports the principle, the development, the microfabrication and the characterization of the 2-dof sensorized end-effector.

silicone/platine (Si/Pt) end-effector, sensorized end-effector, Platine strain gage, micromanipulation, microfabrication, 2 degrees of freedom, force measurement.

1 – INTRODUCTION

In micromanipulation and microassembly applications and in precise positioning in general, the development of microactuators and of integrated actuated microsystems and miniaturized systems has been raising since more than a decade. These existing systems permit to position small objects with a micrometric or even a submicrometric resolution. Among the most used systems are piezoelectric materials based microgrippers^[1-4]. These piezoelectric systems are well appreciated due to the high bandwidth (up to several hundreds of Hz) and the very high resolution of positioning (submicrons) they can offer. Furthermore, the fact that their power is electrical makes their design easier. Finally, piezoelectric materials can also be used as sensors, a property which has been used to develop actuators with self-measurement capability (called self-sensing) in^[5].

Unfortunately, piezoelectric based systems are prone to nonlinearities (hysteresis and creep) which make them finally lose the accuracy although their high resolution. Furthermore, due to the high Q-factor of most of piezoelectric structures and actuators, the microsystems that enclose them exhibit badly damped oscillation which compromise their stability. All these characteristics result in unsuccessful micromanipulation and microassembly tasks. In order to improve the performances of these tasks, closed-loop control techniques have been carried out and successfully applied. These techniques include standard PID (proportional integral derivative) structure or advanced methods such as H-inf, passivity, interval based synthesis and adaptive scheme (see^[6-8] and references herein). However, these control techniques dealt with positioning and force control is not yet well settled. In fact, while control of positioning in mono and multiple degrees of freedom (DoF) is extensively studied, control of force is not, due to the lack of convenient sensors. Visual feedback technique can be used to estimate the force applied by an actuator acting on a manipulated object but this requires a precise knowledge of the property of the object or of the manipulator in order to have a precise estimate of the force. Another technique consists in using integrated gage on the actuator itself but if an end-effector is used for the manipulation, the measurement from the gage could be erroneous if the end-effector's model is not accounted for. External force sensors based on capacitive structures have also been developed^[9]. While their measurement resolution can be very high (up to tens of NanoNewton), the actual versions are hardly utilisable when the actuators are manipulating objects. Furthermore, the above mentioned force measurement techniques utilized in piezoelectric actuators are mostly adapted for one-DoF measurement, i.e. measurement in one axis.

In order to go towards the automation of these actuated microsystems and then to improve the reliability of the above applications, it is necessary that both the position and the force signals brought into play be measured for the feedback. While the study and development of position sensors completely integrated within the actuated microsystems have been emerging these last years ^[10-11], that of integrated force sensors is not really enrolled. In our previous work ^[12], we have demonstrated that combining silicone (Si) as structures and platine (Pt) materials as gage permitted to develop sensorized end-effectors with force sensing that could yield sub-microNewton resolution. The sensorized end-effector is utilizable as mechanical amplifier and adapter between a piezoelectric actuator and a manipulated object as pictured in Fig.1 which depicts an example of one axis force measurement. However, these preliminary results were valuable for one DoF measurement. This paper is motivated by the need to extend the previous Si/Pt sensorized end-effector to 2-DoF in order to permit the measurement of force in two directions during micromanipulation or microassembly applications with sub-microNewton resolution. Several 2-DoF sensorized end-effectors with different dimensions have therefore been microfabricated, with this paper reporting the principle of functioning, the steps of microfabrication and their characterization.

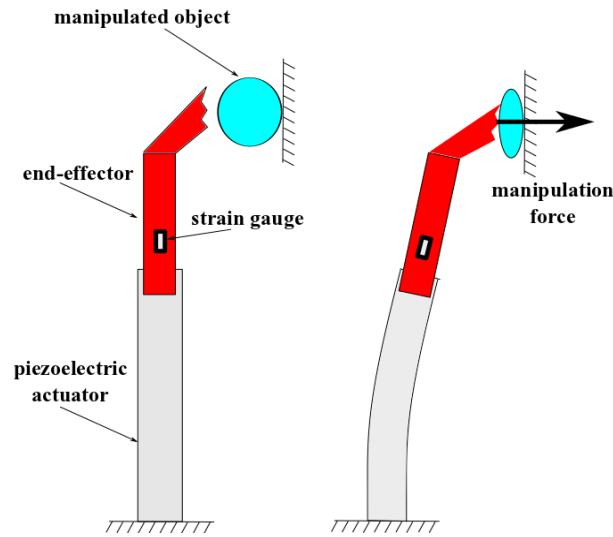


Fig.1 Principle of a piezoelectric actuator with a sensorized end-effector utilized as adapter between the actuator and the manipulated object. The end-effector is equipped with strain gage used to measure the manipulation force.

The remainder of this paper is organized as follows. Section-2 presents the principle of the sensorized end-effector. In section-3, after quickly reporting the microfabrication process, the fabricated structures with different dimensions are presented. Section-4 is devoted to the characterization of the fabricated sensorized end-effectors. Finally, conclusions and perspective works are provided in section-5.

2 – PRINCIPLE OF THE Si/Pt SENSORIZED END-EFFECTOR

Fig.1-a shows the CAD-scheme of the Si end-effector equipped with two embedded Pt strain gage and placed onto an actuator. In our applications, the actuator is a piezoelectric cantilevered actuator capable of bending along two axis (Y and Z). The end-effector serves as interface between the actuator and the manipulated object in order to adapt with the shape of the latter (spheric, parallelepiped,...). When an object is manipulated, both the object and the end-effector are (more or less) deformed. According to the types of manipulated objects, to the type of the actuators and to the range of force to be measured, it is important to well choose the compliance of the end-effector. Thanks to the embedded strain gage sensors, this end-effector can measure with a high resolution the manipulation force both along Y-axis and Z-axis. Fig.1.b pictures a principle scheme of the emplacement of the measurement gage. Two pairs of Pt gage are proposed: the two gage of each pair are distanced of d and c from the central axis of the end-effector and are connected in parallel allowing a high sensitivity measurement along Z-axis (out-of-plane measurement). On the other hand, the two pairs of gage are placed as far as possible from the central axis in order to maximize the sensitivity measurement along Y-axis

(in-plane measurement). More precisely, when a force is applied by the end-effector to an object along the Y-axis, it is deformed in the same direction. Then, the two gage in the left side of the X-axis (see Fig.1.b) are compressed while the two gage in the right side are expanded. By utilizing the difference of resistivity variation of the left and right sides, the force along Y-axis can be estimated. On the other hand, a force along the Z-axis results in the deformation of the end-effector along the same axis, and then a simultaneous compression or simultaneous expansion of the four gage. Hence, the summation of the four resistivity variations provides an estimation of the force along Z-axis. Notice that the four platine piezoresistive sensing elements are placed on the maximum stress area of the deformable silicone structure, i.e. near its embedded extremity.

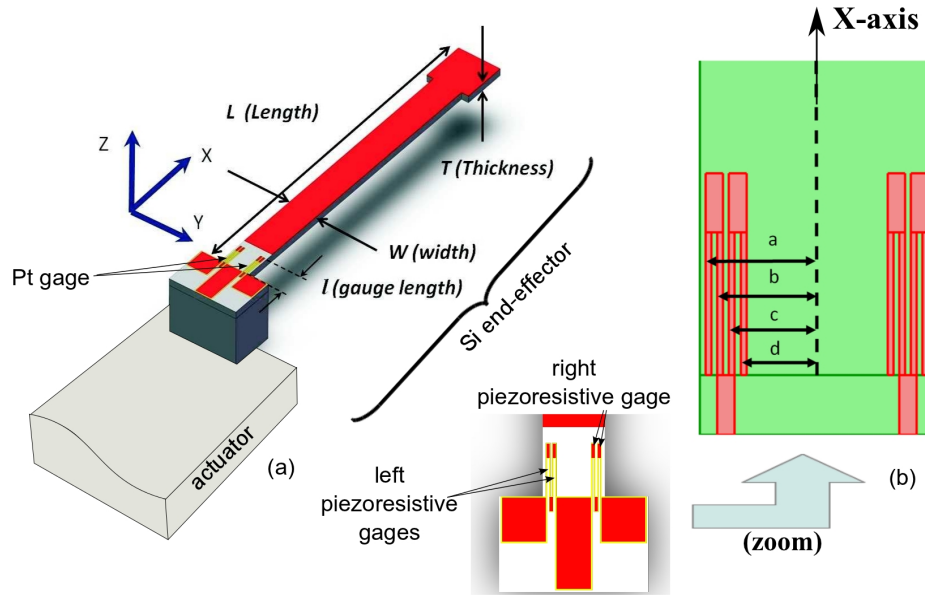


Fig.2. (a): CAD-scheme of a sensorized 2-DoF end-effector.
(b): emplacement of the two pairs of strain gage permitting to measure force in two directions.

3 – MICROFABRICATION OF SENSORIZED END-EFFECTORS

3.1 – Microfabrication process

Fig.3 summarizes the microfabrication process which is splitted into four steps summarized as follows. The first step consists in the settling of the platine gage on the upper surface of the silicone wafer by using Pt sputtering and lift-off techniques. In step-2, the electrodes are settled by using Alu sputtering and lift-off techniques. Finally, step-3 and step-4 consist in structuring the Si end-effector by etching (DRIE) successively the back side and the front side of the wafer.

3.2 – The fabricated end-effectors

Fig.4 (left) pictures samples of fabricated sensorized end-effectors. They possess width of $w=40\mu m$, thickness of $T=25\mu m$ and four different lengths ($L=750\mu m$, $1mm$, $1.5mm$ and $2mm$). Fig.4 (right) pictures a zoom of the gage on one of the end-effectors. Two lengths of Pt gage have been microfabricated and deposited ($l=100\mu m$ to $500\mu m$).

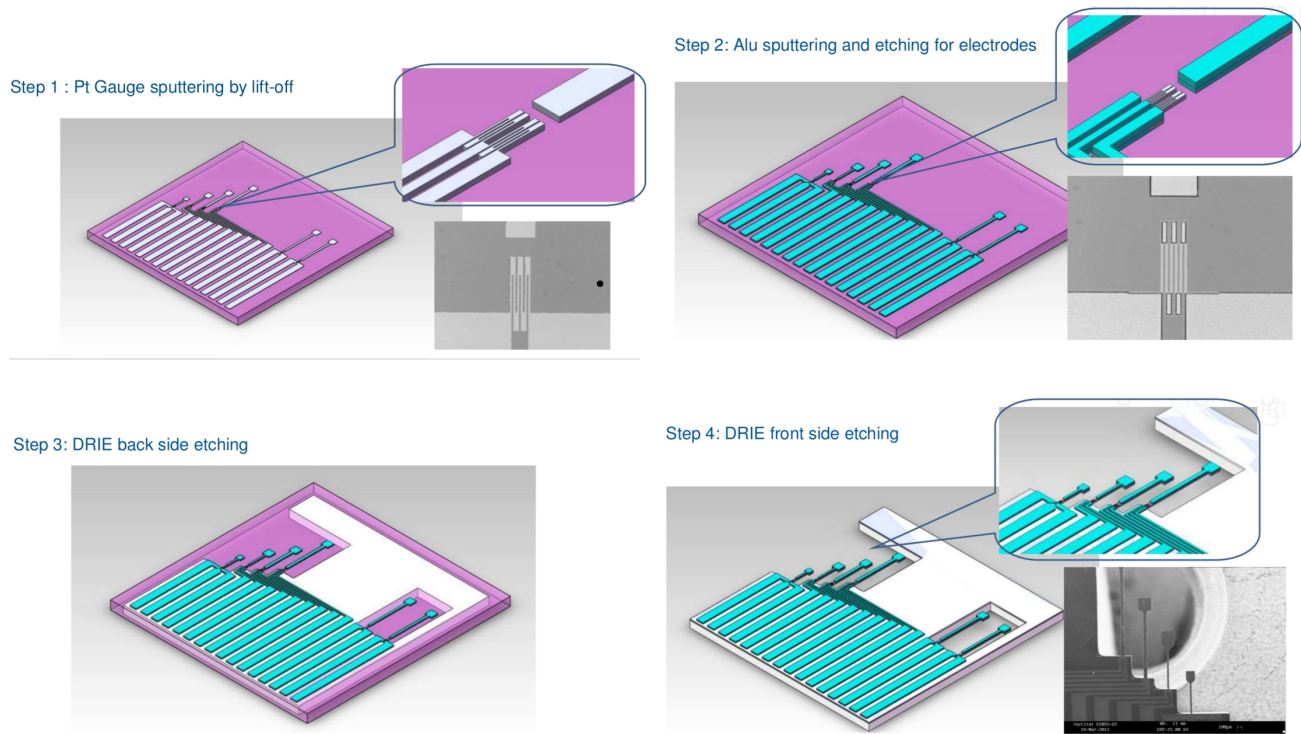


Fig.3 Microfabrication process of the sensorized end-effector based on Si structure and Pt gage.

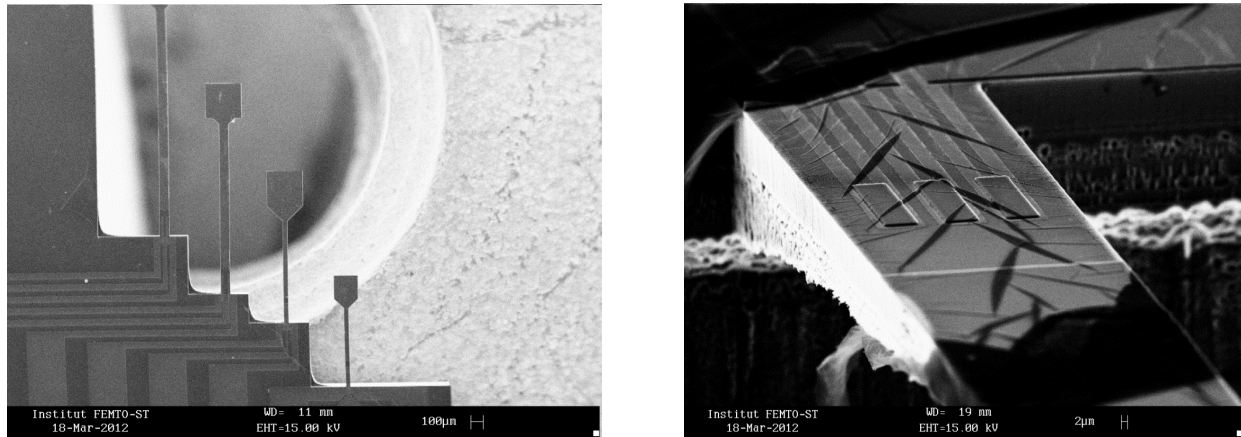


Fig.4 Samples of microfabricated sensorized end-effector (left). Zoom on the Pt gage deposited on one end-effector (right).

4 – CHARACTERIZATION

To characterize the sensitivity of the sensorized end-effector and therefore its performances to measure force, we use the following setup. The tip of a force sensor from Femtotoools company ^[9] is made in contact with the tip of the end-effector in order to stimulate manipulation of object. This is done by pushing the Femtotoools force sensor towards the end-effector thanks to a manual micropositioning table. In the meantime, the

Femtotools force sensor is used to measure the manipulation force and therefore can be used to characterize and to validate the measurement from the gage of the end-effector. The resistance variation of the gage are measured thanks to a precise digital multimeter. Notice that the different sensorized end-effectors with different lengths of gage were characterized successively.

In Fig.5.a is depicted the resistances evolution of the gage when a force along the Y-axis (in-plane) ranging between 0 and 1mN is applied at the tip of the longest sensorized end-effector ($L=2mm$) equipped with the smallest Pt gage ($l=100\mu m$). The circle-line curve corresponds to the resistance of the two gage of the left side while the triangle-line curve corresponds to the resistance of the two gage of the right side. In Fig.5.b is depicted the resistances evolution when a force along the Z-axis (out-of-plane) is applied to the same sensorized end-effector. From these curves, we observe that the left gage and the right gage have almost the same behavior and are all linear. These

figures yield that the sensitivity ($\frac{\Delta R}{R}$) of the sensorized end-effector is of about 0.21% for a range of 1mN in the Y-

axis and of about 0.76% for a range of 1mN in the Z-axis. The corresponding gauge factor ($G = \frac{\Delta R}{R \varepsilon}$, where ε

is the strain of the gage) is about $G=6$. The characterization of the different dimensions of end-effectors with different dimensions of strain gage demonstrate that the sensitivity can reach 0.6% and 0.8% along Y-axis and along Z-axis respectively for the range of measurement (1mN). These characteristics are in good accordance with the requirements of micromanipulation and microassembly applications.

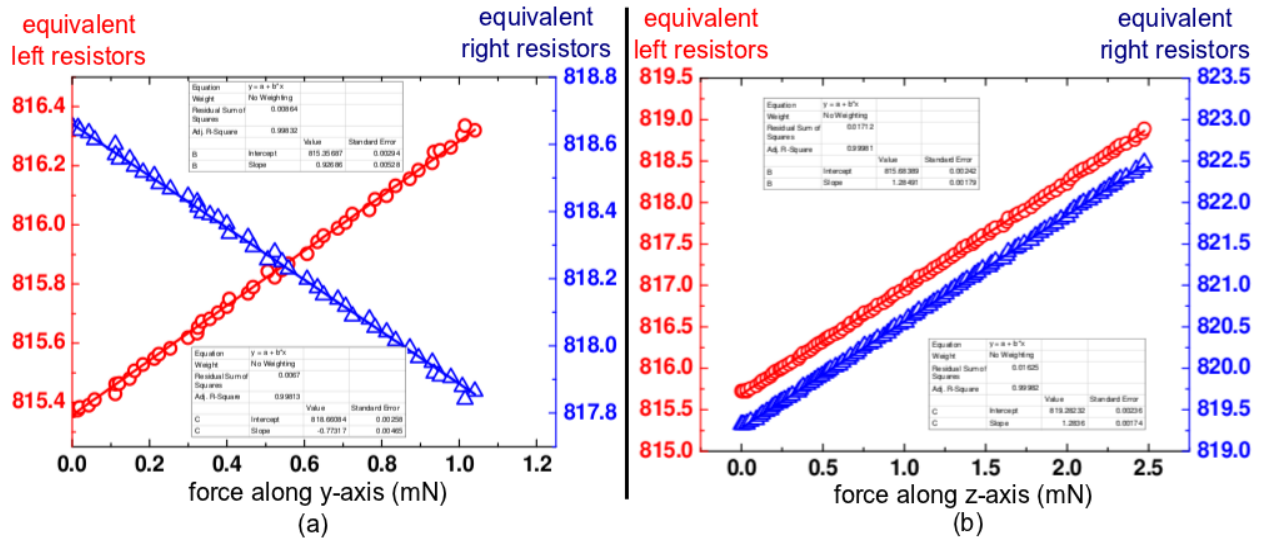


Fig.5. (a): resistances evolution of the Pt gage versus the force along Y-axis. (b): resistances evolution of the Pt gage versus the force along the Z-axis.

5 – CONCLUSION AND PERSPECTIVES

This paper presented the development, the microfabrication process and the characterization of a 2-DoF sensorized end-effector. Based on silicon structure, the end-effector is equipped with four well placed platine gage with a high gauge factor. The sensorized end-effector is therefore able to measure micromanipulation force along two directions (Y-axis and Z-axis). The characterization demonstrates that the sensitivity of the sensors can reach 0.6% and 0.8% for a range of 1mN along the Y-axis and along the Z-axis respectively, with a gauge factor up to $G=6$, which are in agreement with the requirements for micromanipulation carried out at

FEMTO-ST Institute. The integration of the end-effectors onto multiple DoF piezoelectric microgrippers are ongoing and tests on real micromanipulation tasks will be carried out.

ACKNOWLEDGMENTS

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